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A preliminary report on amphibolite-facies, disseminated-replacement-style mineralization at the Madsen gold mine, Red Lake, Ontario¹

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Abstract: Madsen is a disseminated stratabound gold deposit of replacement style located at the deformed unconformity between the Balmer and Confederation assemblages. The deposit comprises two main ore horizons (Austin and McVeigh), hosted by altered mafic volcanoclastic rocks and by (massive and pillowed) basalt flows of the Balmer assemblage metamorphosed at amphibolite grade. A banded-laminated inner core of alteration hosts the ore and is surrounded by an aluminum-rich outer alteration. D_1 is characterized by a bedding-parallel foliation and D_2 , the main phase, is characterized by an S_2 foliation, local sinistral shearing, and F_2 folds. The alteration and mineralization have been deformed by the D_2 structures. The deposit is early or pre- D_2 and was formed between 2744 ± 1 Ma, the age of a quartz-feldspar porphyry, and 2699 ± 4 , the age of a post-ore dyke. Madsen shares some features analogous with higher temperature (400 to 600°C) gold deposits as well as gold skarns hosted by mafic rocks.

Résumé : Le gisement de Madsen est un gisement d'or disséminé stratoïde de type remplacement qui est situé à l'emplacement de la discordance déformée séparant les assemblages de Balmer et de Confederation. Il comporte deux horizons aurifères principaux (Austin et McVeigh) encaissés dans des roches volcanoclastiques mafiques altérées et des coulées basaltiques (massives et en coussins) de l'assemblage de Balmer métamorphisées au faciès des amphibolites. Le minerai est localisé dans un noyau interne laminé-rubané d'altération qu'entoure une zone externe d'altération riche en aluminium. La déformation D_1 est caractérisée par une foliation parallèle au litage et la déformation principale D_2 , par une foliation S_2 , un cisaillement sénestre local et des plis P_2 . L'altération et la minéralisation sont déformées par les structures associées à D_2 . Le gisement a été formé au début de la déformation D_2 ou avant, soit entre 2744 ± 1 Ma, l'âge d'un porphyre quartzofeldspathique, et 2699 ± 4 Ma, l'âge d'un dyke postérieur à la minéralisation. Il présente des éléments semblables à ceux d'autres types de gîtes encaissés dans des roches mafiques, à savoir les gisements aurifères de plus haute température (de 400 à 600 °C) et les skarns aurifères.

¹ Contribution to the Western Superior NATMAP Project

INTRODUCTION

The Red Lake greenstone belt is one of the largest gold districts in Canada with more than 570 t of gold produced since 1930. The Madsen mine, the second largest deposit in the district, produced 75.16 t of gold and 12.99 t of silver from 1938 to 1976 from ore with an average grade of 10 g/t Au and 1.7 g/t Ag (Durocher, 1983). The deposit is currently being mined and explored by Claude Resources.

The Madsen Mine is located in Baird Township, 8 km south of the town of Red Lake, Ontario. The deposit illustrates some of the geological characteristics of other deposits in the district, including proximity to a late granodiorite batholith, amphibolite-facies metamorphism, replacement-style mineralization, aluminous and potassic hydrothermal alteration, and ore hosted by tholeiitic basalt adjacent to ultramafic rocks. In the summer of 1999, as part of the Western Superior NATMAP Project, we mapped and logged drill core both on surface and underground at the McVeigh and Austin zones. In order to better understand the origin, key parameters, and geometry of the deposit, the objectives of this study were to 1) better define the nature and zonation of gold-bearing hydrothermal alteration, and 2) determine the timing of, and relationship between, gold mineralization and deformation. This report presents preliminary field-based observations and interpretations.

GEOLOGICAL SETTING

The Madsen gold deposit is located in the Red Lake greenstone belt, Uchi Subprovince (Superior Province). The area was mapped by Horwood (1940), Ferguson (1965), Durocher (1983), Hugon and Schwerdtner (1984), and Wallace and Atkinson (1993). Wallace (1981) indicated that the deposit area is located on the southeast-facing, southern limb of a large fold or domal structure. The strike and dip of the units define an open S-shaped flexure, whereas the foliations generally strike 045–060° and dip southeast (70–75°) (Durocher, 1983).

The Madsen mine area comprises two volcanic-dominated assemblages: the 2.99–2.96 Ga Balmer assemblage to the northwest, and the 2.75–2.73 Ga Confederation assemblage to the southeast (Corfu and Wallace, 1986; Corfu and Andrews, 1987). The deposit is hosted by two lithotectonic units within the Balmer assemblage that are historically referred to as the 'Austin tuff' (including the South Austin ore zone) and McVeigh 'tuff' (Durocher, 1983; Fig. 1). These two units are located at or close to the boundary between the Balmer and Confederation assemblages, respectively (Fig. 1; see Fig. 12 in Sanborn-Barrie et al., 2000). We interpret this boundary as a deformed and altered angular unconformity which represents a time gap of up to 250 million years, and extends across the southeast part of the belt through the Madsen and the Starratt-Olsen mines (see also Sanborn-Barrie et al., 2000). Rocks in the Madsen area have been metamorphosed to amphibolite facies, and are a contact

thermal aureole around the 2704 ± 1.5 Ma Killala–Baird batholith (Durocher, 1983; Lavigne et al., 1986; Corfu and Andrews, 1987).

The footwall of the Madsen deposit consists of the Balmer assemblage, which is dominated by tholeiitic pillowed basalt and gabbro interbedded with thin peridotitic and basaltic komatiite units (Pirie, 1982; Durocher, 1983). An intrusive complex composed of peridotite, pyroxenite, and gabbro is located in the immediate hangingwall of the McVeigh tuff. Thin units of talc schist constitute the hanging wall of the McVeigh and South Austin tuffs and footwall of the Austin tuff (Horwood, 1940; Ferguson, 1965). The Austin and McVeigh ore horizons (or tuffs) are several kilometres long and have been variably interpreted as altered dacitic pyroclastic rocks (Horwood, 1940), heterogeneous sequences of hydrothermally altered and deformed mafic flows and intermediate to felsic pyroclastic rocks (Durocher, 1983), mylonites (Hugon and Schwerdtner, 1984), and altered and deformed mafic flows (Lavigne et al., 1986). Our surface mapping indicates that the McVeigh tuff corresponds to hydrothermally altered and heterogeneously deformed massive and pillowed basalt, whereas the Austin tuff is best described as a composite unit of hydrothermally altered and heterogeneously deformed mafic volcanoclastic, epiclastic (wackes and conglomerates), and local mafic volcanic rocks. We interpret the McVeigh horizon to occur within the Balmer assemblage and the Austin horizon to represent, at least in part, hydrothermally altered fragmental rocks that mark an unconformity between the Mesoproterozoic Balmer and Neoproterozoic Confederation assemblages (Fig. 1).

The immediate hangingwall of the Austin tuff is a quartz-feldspar-porphyrific, lapilli-crystal tuff, with 10–25% quartz phenocrysts (2–5 mm), 5–10% feldspar phenocrysts (1–3 mm) in a sericitized quartzofeldspathic matrix (Fig. 1, 4a). This tuff contains 2–3% lithic fragments concentrated near its base in centimetre-wide horizons defining bedding. The quartz-feldspar-porphyrific, lapilli-crystal tuff forms the basal part of the Confederation assemblage and is dated at 2744 ± 1 Ma (Corfu and Andrews, 1987) (Fig. 1).

A feldspar-porphyrific lapilli tuff with 12–15% feldspar and 3–5 % quartz overlies the quartz-feldspar-porphyrific, lapilli-crystal tuff, and locally contains lithic fragments of it. A weakly deformed, discontinuous gabbro sill-dike complex is located in the hanging wall of the feldspar-porphyrific lapilli tuff.

Fragmental rocks interpreted to be clastic and/or epiclastic in origin occur at several stratigraphic levels in the mine area. They form part of the Austin tuff horizon immediately underneath the base of the Confederation assemblage (see Fig. 15b in Sanborn-Barrie et al., 2000), and occur within the lower Confederation assemblage, between the quartz-feldspar-porphyrific, lapilli-crystal tuff and feldspar-porphyrific lapilli tuff (see also Fig. 15a in Sanborn-Barrie et al., 2000) and stratigraphically above the feldspar-porphyrific lapilli tuff (Fig. 1). Within the Confederation assemblage, polymictic conglomerate is clast supported and contains mafic volcanic and sedimentary clasts (20–30 cm long) in a mafic-dominated matrix. Both the mafic clasts

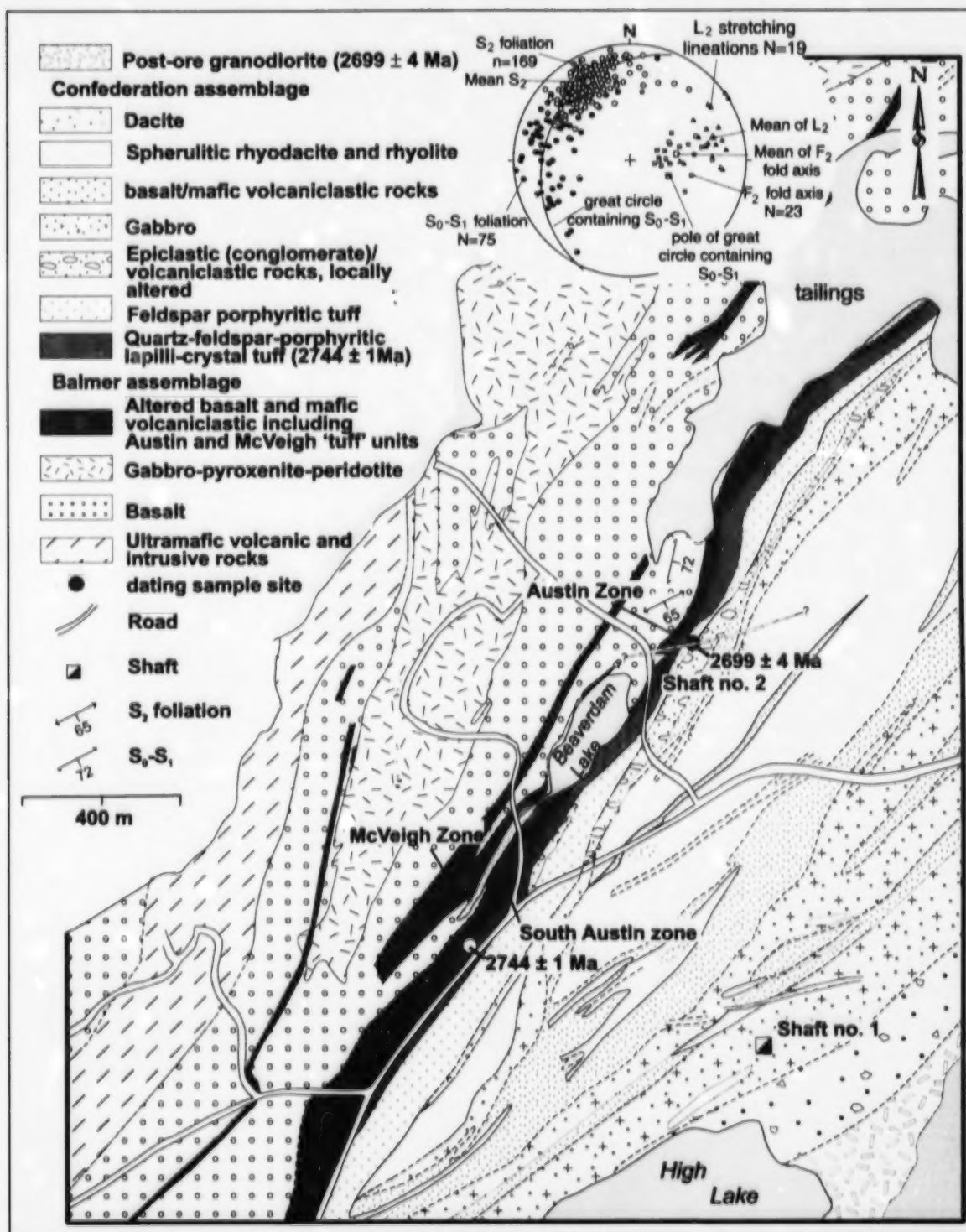


Figure 1. Geology of the Madsen mine area (modified from Lavigne et al., 1986). Stereoplots are equal area projections (lower hemisphere).

and the matrix contain abundant garnet (20–30%). Some feldspar-porphyritic and quartz-feldspar-porphyritic felsic volcanic clasts are also present. The conglomerate also contains 3–5% clasts with 30–50% andalusite and some biotite. Local interbedded fine-grained sediments are andalusite rich and contain tourmaline. Local graded bedding and scour structures indicate southeast younging, consistent with younging throughout the Confederation assemblage in the area (see Fig. 12 in Sanborn-Barrie et al., 2000). Farther to the southeast (up-section), spherulitic dacite with abundant metamorphic garnet forms a succession several hundred metres thick.

A large number of centimetre- to metre-wide, unaltered, most-commonly unstrained, locally zoned, diorite-granodiorite dikes cut across all lithological units, including the Austin and McVeigh ores (Horwood 1940; McIntosh 1948; this study). These dykes strike northwest and their dip varies from shallow to steep (McIntosh, 1948). One such dike has a U-Pb (titanite) age of 2699 ± 4 Ma (Corfu and Andrews, 1987). This age is marginally younger than a granitoid batholith to which it may be related, the 2704 ± 1.5 Ma Killala-Baird batholith (Corfu and Andrews, 1987). The Faulkenham Lake granodiorite stock, southeast of Madsen, is also correlated with this magmatic suite (Durocher, 1983) (see Fig. 2 in Sanborn-Barrie et al., 2000).

Although Ferguson (1965) indicates that there is no strong shear zone present in the area, Hugon and Schwerdtner (1984) and Lavigne et al. (1986) stressed that the Madsen deposit is centred within a heterogeneous, sinistral shear zone, up to 100 m wide, corresponding to the Austin tuff. Hugon and Schwerdtner (1984) renamed the Austin tuff the 'Austin Shear Zone', and indicated that it belongs to the Flat Lake-Howey Bay Deformation Zone. Furthermore, they interpret the Austin Shear Zone to be synchronous with deformation and metamorphism related to the emplacement of the Killala-Baird batholith (Hugon and Schwerdtner, 1984).

STRUCTURE

The intensity of the deformation is heterogeneous, but overall is low to medium, with local centimetre- to metre-scale higher strain zones. Two main generations of structures are documented, namely D_1 and D_2 . D_1 is characterized by a weakly developed bedding-parallel foliation (S_0 - S_1) generally trending north-northeast and dipping to the southeast (mean: $012/62^\circ$) (Fig. 1). However, the foliation trend is variable and poles to S_0 - S_1 are distributed on a great circle (Fig. 1). Although generally weak, in the few locations where the Austin tuff was visited underground, a relatively intense foliation interpreted to be S_0 - S_1 was recorded. This suggests that the S_0 - S_1 foliation is locally more intense, especially in the talc schist of the footwall.

D_2 represents the main phase of deformation developed in the Madsen deposit area. It is characterized by a moderately developed, east-northeast-trending S_2 foliation that is southeast dipping (mean: $063/65^\circ$; Fig. 1). The S_2 foliation locally contains a weakly developed L_2 stretching lineation with a

shallow to moderate eastward plunge (mean: $074/27^\circ$; Fig. 1). Strain markers deformed by D_2 have an aspect ratio of about 2:1 (XY plane), suggesting that the strain is mainly a flattening strain ($L < S$), with local zones of LS tectonites. S_2 is axial planar to local F_2 folds deforming both S_0 - S_1 and quartz veins (Fig. 4b). F_2 folds have an asymmetric 'S' shape and plunge shallowly to moderately toward the east-northeast (mean: $083/57^\circ$). The pole of the great circle containing the S_0 - S_1 foliation is close to the measured axes of minor F_2 folds (Fig. 1).

The intensity of the S_2 foliation is typically moderate, but varies from a weak to a penetrative schistosity, particularly near the contact between the footwall and hanging wall of the Austin tuff. The quartz-feldspar-porphyritic, lapilli-crystal tuff has recorded significant D_2 strain reflected by the commonly well developed S_2 foliation, as well as by centimetre- to metre-wide shear zones which are observed close to its contact with the Austin tuff. The shear zones (mean $060/70^\circ$) record an increase in strain intensity toward the Madsen ore as reported by Lavigne et al. (1986). They show small-scale C-S fabrics indicating a sinistral component of motion as noted by Hugon and Schwerdtner (1984). Weak L_2 stretching lineations plunge shallowly to the east (Fig. 1), and are compatible with a sinistral component of shearing. However, widespread preservation of primary textures and obliquity between S_0 - S_1 and S_2 cleavage within the Austin tuff and quartz-feldspar-porphyritic, lapilli-crystal tuff indicate that strain was moderate (see Fig. 15b in Sanborn-Barrie et al., 2000). There is no indication of a regional scale major D_2 shear zone or mylonites (cf. Hugon and Schwerdtner, 1984) associated with the Austin and McVeigh ore zones.

Horwood (1940) indicated that ore zones at Madsen comprise several en échelon orebodies consisting of lenses of sheared sulphide-bearing tuff. The enveloping surface of the ore lenses is subparallel to bedding, whereas the individual ore lenses are oblique and parallel to foliation (Durocher, 1983) (Fig. 2). These geometric relationships are consistent with folding, disruption, and transposition of the Austin and McVeigh ore zones by the D_2 phase of deformation. Locally, tourmaline-garnet-rich layers and amphibole-biotite metasomatic bands were folded by F_2 and partly crenulated by S_2 . In drill core, calcite veinlets with amphibole alteration selvages and biotite±sulphide bands are locally crenulated by S_2 . A veinlet of visible gold from a high-grade stope of the McVeigh zone is crenulated by S_2 .

At the deposit scale, there is a spatial relationship between the economic ore zone(s) within the Austin tuff and 'rolls' (Horwood, 1940; McIntosh, 1948; Butler, 1955). These rolls exhibit apparent increases in thickness of the Austin tuff, and correspond to the hinges of F_2 folds as indicated by the sympathetic change in the geometry of the quartz-feldspar-porphyritic, lapilli-crystal tuff, Austin tuff and talc schists. This is well illustrated on Horwood's (1940) geological compilation (Fig. 2), where the sympathetic change in orientation of the ore relative to the hanging wall and footwall, on the 350 and 500 foot levels, is consistent with the F_2 fold geometry. The ore zones and enveloping lower grade mineralization are folded (Fig. 3), with limbs of the folds showing disruption and transposition of the ore lenses along

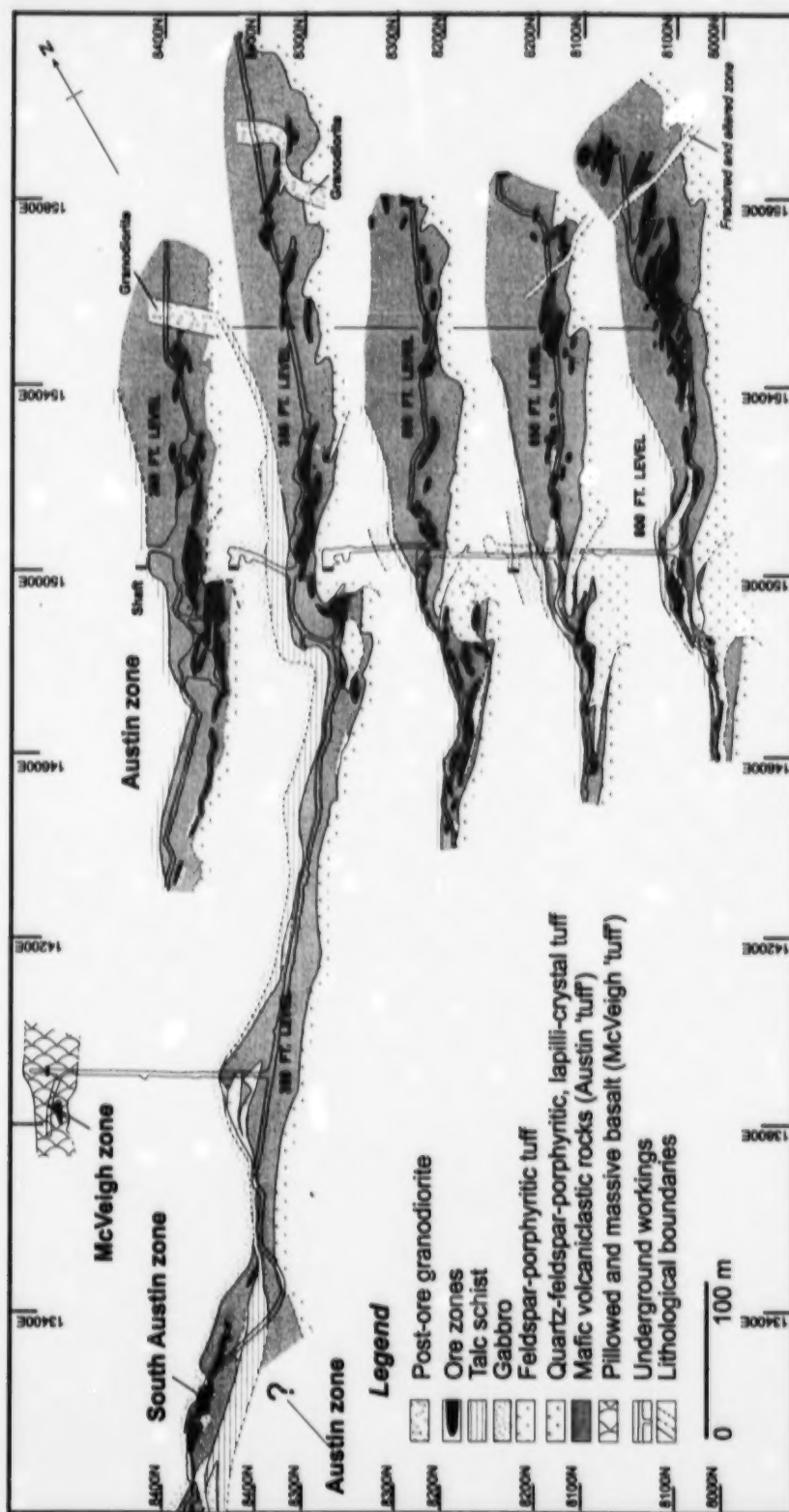


Figure 2. Composite plan showing the geology and ore distribution of the Madsen mine (adapted from Horwood, 1940).

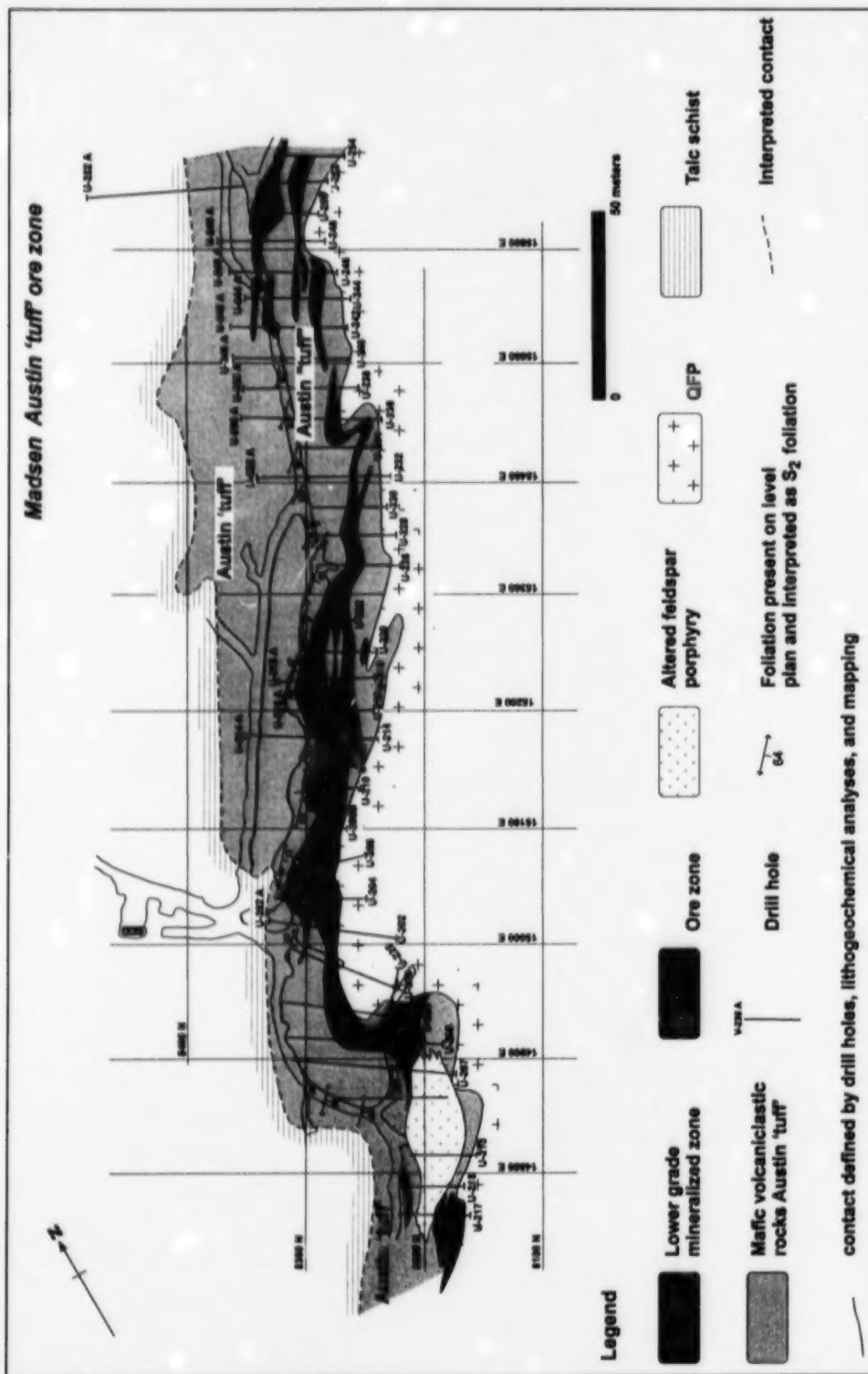


Figure 3. Geology of the second level of the Madsen Mine (adapted from a 1:20 scale geology map of the mine). QFP – quartz-feldspar-porphyrific, lapilli-crystal tuff.

the S_2 fabric, as illustrated on the 800 foot level between 15200E and 15800E (Fig. 2). A compilation by Zhang (unpub. company rept., 1996) of the variation in orientation of the contact between the Austin tuff and quartz-feldspar-porphyrific, lapilli-crystal tuff on levels 1 and 2 of the mine has also defined such folding. The moderately steep eastward plunge of the ore shoot in the Austin zone is colinear to the plunge of F_2 folds described above (Fig. 1). However, the plunge of the Austin and McVeigh ore shoots varies along strike, possibly as a result of variable transposition of the ore zones by D_2 structures. The S-shaped of the F_2 folds in plan view suggests that these folds are compatible with a sinistral sense of motion during D_2 . These F_2 folds may represent intrafolial folds confined within the mafic volcanoclastic-volcanic rocks hosting the ore. The location of these intrafolial F_2 folds was controlled by the primary (bedding) and secondary (hydrothermal layering) anisotropy, and the competency contrast between these units and the quartz-feldspar-porphyrific, lapilli-crystal tuff.

ALTERATION/MINERALIZATION

The Madsen deposit is a stratabound, replacement-style, disseminated gold deposit (e.g. Poulsen, 1996). It contains at least four different ore zones: the Austin, South Austin, McVeigh, and No. 8 Vein (Fig. 1, 2). No. 8 Vein is a high-grade quartz vein hosted by talc schist and represents the only known example of vein-type ore in the deposit. It has been mined more than 1 km below surface. Another 'tuff' unit is present in the Confederation assemblage in the hanging wall of the feldspar-porphyrific lapilli tuff (Fig. 1). This tuff is dominated by metamorphosed sediments and is locally hydrothermally altered and contains andalusite, biotite, and amphibole, but no significant gold mineralization.

The hydrothermal alteration at Madsen comprises variable proportions of andalusite, staurolite, garnet, chloritoid, biotite, and quartz (Andrews et al., 1986). Our study indicates that the deposit is characterized by two alteration facies now corresponding to metamorphic assemblages: 1) an aluminous outer zone, and 2) an inner alteration zone. The transition between the two alteration zones is gradual. The aluminous outer zone coincides with the strong sodium depletion, whereas the inner alteration zone corresponds with the potassic enrichment documented by Durocher (1983).

Aluminous outer alteration

The aluminous outer alteration is barren to anomalous in gold and is characterized by metre- to tens-of-metres-wide replacement zones with assemblages of andalusite, garnet, biotite, staurolite, and amphibole that alternate with metre-wide zones of intense stockwork veining. These two styles of alteration are especially well developed in the vicinity of the McVeigh portal, where strongly altered pillowed basalt units occur in the immediate hanging wall of the ore. Pillow rims and interpillow hyaloclastite are altered to amphibole (actinolite/hornblende) $\pm$ calcite with traces of garnet and disseminated sulphide minerals. The pillows are

intensely altered and replaced by fine-grained biotite, andalusite, garnet, staurolite, and locally, actinolite and muscovite (Fig. 4c). Andalusite form disseminated crystals, up to 1 cm long, or semimassive aggregates (Fig. 4d). Garnet (1–3 mm) is present as euhedral crystals and as centimetre-scale aggregates that may account for as much as 20–30% of the rock (Fig. 4e). Modal variations in the alteration minerals locally impart a layered aspect to the rock. Locally, the cores of the garnet crystals are replaced by pyrrhotite and/or pyrite. Staurolite is present as fine, disseminated crystals. Chloritoid and traces of chlorite are also locally present.

The 'stockwork' zones consist of randomly oriented millimetre-wide fractures, filled with green amphibole (hornblende/actinolite). These cut altered, biotite $\pm$ garnet-bearing pillow basalt (Fig. 4f). The stockwork veinlets are confined to pillow interiors, whereas the rims are replacement-filled by green amphibole with some traces of sulphides.

The strain in the outer alteration zone is generally very low. The pillows are only slightly flattened parallel to the S_0 - S_1 fabric. Locally, the andalusite and garnet are elongate parallel to S_0 - S_1 or S_2 . Biotite and muscovite locally define a well developed foliation (S_0 - S_1 and/or S_2).

Inner alteration

The inner alteration zones are metres to a few tens of metres wide, and enclose discrete ore zones. The inner zone is characterized by a metasomatic layering producing a banded-laminated texture, produced by replacement, impregnations, and fracture filling. These bands are commonly foliated by S_0 - S_1 and/or S_2 . The banded-laminated texture is defined by discontinuous millimetre- to a few centimetre-wide amphibole-rich bands alternating with biotite-rich layers (Fig. 5a). These layers are sometimes very irregular, creating a stockwork or breccia texture (Fig. 4g, 5b, c). The amphibole-rich bands are composed of a diversity of minerals including actinolite, hornblende, microcline, calcite, and tourmaline. The amphibole is commonly randomly oriented, whereas biotite-rich layers, containing up to 25% biotite, display a lamination-parallel foliation (S_0 - S_1 and/or S_2). The biotite is in a fine-grained, recrystallized, quartz-rich matrix with calcite and muscovite. A greenish mineral, interpreted as diopside, locally forms disseminated crystals up to 7–8 cm long, or veinlets.

Andalusite and staurolite are typically absent, whereas traces to a few per cent of garnet and clinozoisite are locally present in the inner alteration zones. The sulphides (trace to 3%) are disseminated and mainly composed of pyrite and pyrrhotite with traces of chalcopryrite, sphalerite, and magnetite, and locally, realgar and orpiment (e.g. Butler, 1955).

Within the inner alteration zones, the Austin and McVeigh ore zones comprise several lenses known as the footwall, main, and hanging-wall zones, surrounded by discontinuous lower grade mineralization. These ore zones are up to a few metres wide and are characterized by a well layered or commonly finely laminated character, as well as a common increase in sulphide content (Fig. 5d). The sulphide

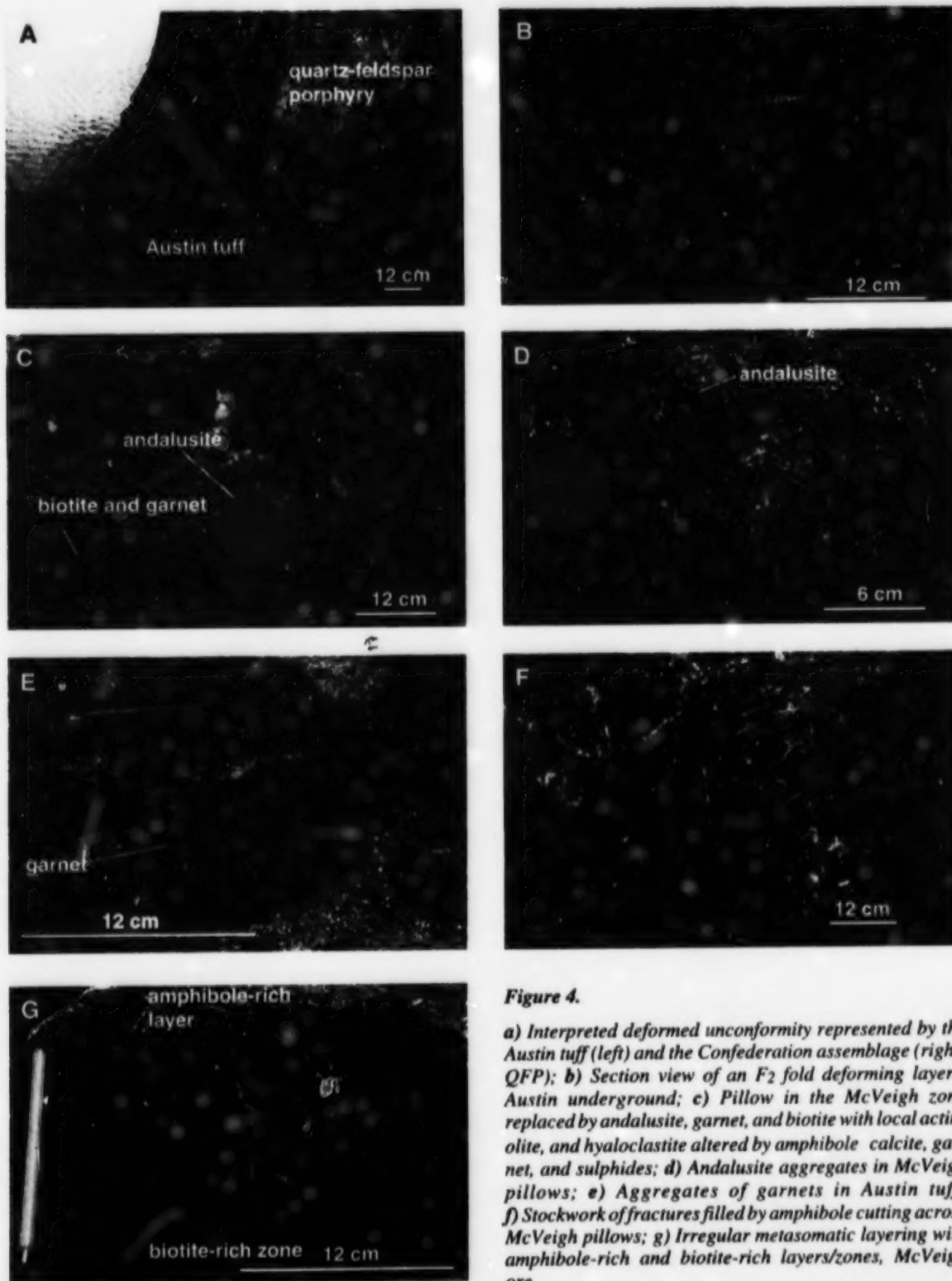


Figure 4.

a) Interpreted deformed unconformity represented by the Austin tuff (left) and the Confederation assemblage (right; QFP); b) Section view of an F₂ fold deforming layers, Austin underground; c) Pillow in the McVeigh zone replaced by andalusite, garnet, and biotite with local actinolite, and hyaloclastite altered by amphibole calcite, garnet, and sulphides; d) Andalusite aggregates in McVeigh pillows; e) Aggregates of garnets in Austin tuff; f) Stockwork of fractures filled by amphibole cutting across McVeigh pillows; g) Irregular metasomatic layering with amphibole-rich and biotite-rich layers/zones, McVeigh ore.

minerals, locally up to 8–10%, are mainly composed of pyrrhotite, pyrite, and/or arsenopyrite, with traces of chalcopyrite, as disseminations or veinlets parallel to the laminations/foliations. Sulphide-rich (10–30%) pyrite-bearing lenses or bands are barren of gold. Local zones with 10–15% disseminated arsenopyrite contain up to 120 g/t Au over tens of centimetres. These high-grade zones are more siliceous, with millimetre-wide layers/bands of quartz alternating with muscovite-, quartz-, and tourmaline-rich bands with disseminated arsenopyrite.

Most of the gold occurs in its native state as small micrometre-sized inclusions in silicate minerals, and locally as coatings on sulphide minerals (Ferguson, 1965). The metallic signature of gold mineralization is characterized by high Au, Ag, As±Zn, Sb, Cu, and Hg values (Durocher, 1983).

Small quartz veinlets subparallel to the metasomatic layering and discordant breccias are only locally present in the ore zone and rarely contain significant gold. Centimetre- to metre-wide zones of more siliceous alteration are also common within the ore zones. This more siliceous alteration is composed of irregular bands or layers of quartz, biotite, muscovite, and microcline as replacement impregnations or

veinlets. Such a siliceous alteration probably represents the most intensely altered part of the system. These zones are well preserved in the McVeigh ore zone, where visible gold is commonly present as fine disseminations or veinlets within the more biotite-siliceous-rich alteration zones, as well as within amphibole-rich bands-layers containing pyrrhotite or pyrite. The presence of highly foliated and sericitized quartz-feldspar-porphyritic, lapilli-crystal tuff/feldspar-porphyritic lapilli tuff is also common at the contact or within the ore zones (Butler, 1955). The competency contrast between the ore hosts and the above-mentioned tuff units may have induced a secondary permeability promoting enhanced fluid circulation and higher gold values.

The proportion of carbonate is highly variable, but there is a spatial relationship between carbonate alteration (calcite) in the inner alteration and gold mineralization. This spatial relationship is illustrated by an increase in calcite, as disseminations and veinlets towards the ore zone. However, the ore itself is generally calcite free. The presence of a strong carbonate alteration halo is commonly indicative of proximity to a higher grade zone. This is particularly well illustrated where calcite-quartz veins and carbonatized rocks are cut across by 1–2 cm wide, biotite-rich, black 'lines' where visible gold occurs as fine disseminations in adjacent laminated

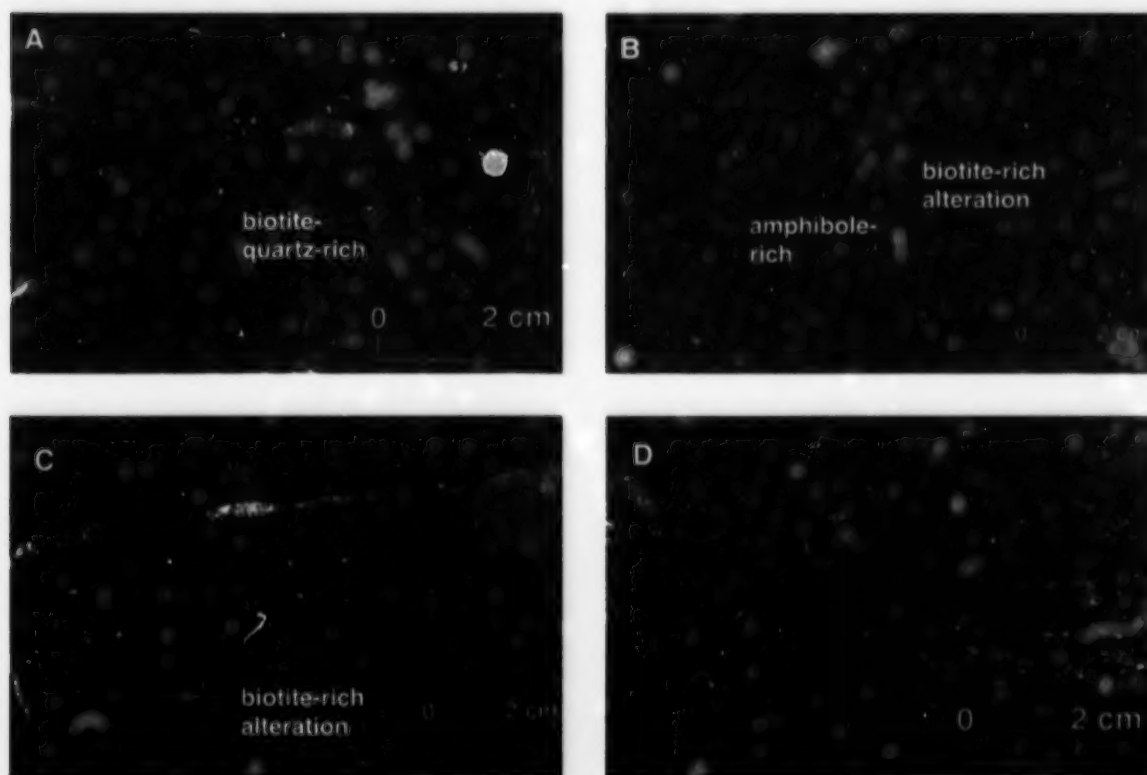


Figure 5. a) Layered texture in McVeigh ore zone with biotite-quartz-rich and amphibole-rich bands; b) Stockwork or metasomatic front in McVeigh ore with biotite-rich alteration infilling and replacing amphibole-rich alteration; c) Breccia-like texture in McVeigh ore with biotite-rich laminated-foliated alteration and amphibole-rich remnants; d) Laminated and highly foliated sulphide-rich McVeigh ore.

biotite-amphibole-rich rocks. These black lines share some features analogous with the black line faults at the Campbell Mine (e.g. Penczak and Mason, 1997).

Tourmaline is commonly present, although not restricted to the inner alteration zones. Tourmaline-rich layers parallel to the layering-banding and quartz-tourmaline veinlets are present within the aluminous outer zones and elsewhere in non-altered pillow basalt distant from the McVeigh tuff, consistent with the large-scale boron anomaly documented by Durocher (1983).

The intensity of the foliation within the inner alteration zone is heterogeneous and varies from poorly developed to a more commonly well defined fabric (S_0 - S_1 or S_2) subparallel to the laminations. The metasomatic layered aspect of the ore and alteration is one of the most characteristic features of the mineralization at Madsen. It is possible that the layering of the inner alteration is, at least in part, produced by flattening of the original metasomatic layering, stockwork, or breccia aspect of the alteration into the foliation. Examples of nonfoliated, partly foliated, and highly foliated ore are present (Fig. 5b, c, d) consistent with heterogeneous strain. Such variations in foliation intensity may reflect variable amounts of transposition of original textures into the S_1 or more probably the S_2 foliation. Crenulation of alteration bands, sulphides and calcite veinlets by the S_2 foliation as well as the large-scale deformation and folding of the Austin ore by F_2 folds (Fig. 3) are consistent with pre- to early D_2 timing of gold mineralization.

DISCUSSION AND CONCLUSION

The Madsen gold deposit, located at the interface between the Balmer and Confederation assemblages, was formed between 2744 ± 1 Ma, the age of the quartz-feldspar-porphyrific, lapilli-crystal tuff, and 2699 ± 4 Ma, the minimum age of a crosscutting post-ore dyke (Corfu and Andrews, 1987).

Aluminous assemblages of basalts are interpreted as the metamorphosed product of strong hydrothermal leaching and can be used as an exploration tool to locate and navigate within the hydrothermal system. On the other hand, andalusite- and garnet-bearing clasts within conglomerate, and andalusite-rich, fine-grained sedimentary rocks in the Confederation assemblage may simply represent isochemical metamorphism of unaltered pelitic sediments. An ongoing petrographic study will help distinguish mineral assemblages produced by metamorphism of sediments versus metamorphism of hydrothermally altered rocks as well as the timing of metamorphism. Porphyroblasts of andalusite and garnet within the alteration zones and in Confederation-age meta-sedimentary rock commonly define the S_2 foliation, and locally define S_0 - S_1 (see Fig. 13 in Sanborn-Barrie et al., this volume). These relationships contradict earlier interpretations that relate porphyroblast growth to D_2 during emplacement of the ca. 2704 Ma Killala-Baird batholith and raise questions concerning the chronology of hydrothermal alteration(s), metamorphism, and deformation.

The Madsen gold deposit is spatially associated with more intensively developed zone(s) of D_2 strain, although field relationships indicate that alteration and mineralization in the deposit are deformed by D_2 structures and consequently are early or pre- D_2 . The spatial relationship between F_2 fold hinges and ore grade suggests that remobilization during D_2 may have played a key role in the formation of economic mineralization. Although, the timing of alteration responsible for the aluminous alteration is pre- to syn- D_1 , the relationship of gold mineralization to this hydrothermal alteration is not yet known.

Primary permeability was an important element in the formation of the deposit as seen in the stratabound geometry and physical location of both ore zones at, or close to, the boundary between the Balmer and Confederation assemblages. An angular unconformity between the Balmer and Confederation assemblages (see also Sanborn-Barrie et al., 2000) is believed to have potentially provided a more permeable channel for mineralizing fluids. Furthermore, the competency contrast between the quartz-feldspar-porphyrific, lapilli-crystal tuff and the Austin tuff may be responsible for strain localization at that rheological boundary, and induced a secondary permeability allowing greater access to the hydrothermal gold-bearing fluid.

The mafic composition of both the Austin and McVeigh ore zones played an important role by acting as an Fe-Mg-Ca-rich trap that reacted with the auriferous fluid, inducing precipitation of gold and the stratabound replacement style of mineralization.

The style of mineralization and mineralogy at the Madsen deposit clearly indicate that this is not a typical greenstone gold deposit. Madsen rather shares similarities with a highly controversial group, in term of genesis and controls, of higher temperature (400 to 600°C) gold deposits hosted by mafic rocks in Australia (e.g. McCuaig et al., 1993; Neumayr et al. 1993; Witt and Vanderhor, 1998). The disseminated nature of the ore, composition of host rocks, presence of biotite, microcline, garnet, calcite, amphiboles, pyrrhotite, and arsenopyrite, as well as the location of the deposit in the thermal aureole of the Killala-Baird batholith are all characteristic features of syn-amphibolite-facies epigenetic orogenic gold deposits (e.g. Neumayr et al., 1993; Witt and Vanderhor, 1998). However, unlike the Australian examples, there is no evidence of a major ductile shear zone in the Madsen area. If the deposit is centred on a higher order structure related to a first-order major fault, the latter as yet to be found in the area mapped. The key element is that the D_2 structures that represent the main deformation event in the Madsen area are late to post-mineralization. Based on its style and mineralogy, the deposit also shares significant analogies with gold-skarn deposits hosted by mafic volcanic rocks.

It has been proposed that batholith intrusion, thermal metamorphism, alteration, shear deformation, and gold mineralization in the Madsen area were all broadly coeval and genetically related to emplacement of the Killala-Baird batholith at 2704 ± 1.5 Ma (Andrews et al., 1986; Corfu and Andrews, 1987). Furthermore, the Madsen deposit is envisioned by these authors to represent a deeper, higher

temperature equivalent of vein-type deposits present elsewhere in the Red Lake camp (Andrews et al., 1986). However, the absence of significant homogeneous ductile strain may indicate that the deposit was not formed deep in the crust. Furthermore, the presence of a postductile deformation and post-ore granodiorite dike with an age of 2699 ± 4 Ma suggests that a genetic relationship with the Killala-Baird batholith remains highly equivocal, as the range of possible ages of the dike (2695–2703 Ma) overlaps with the possible ages of the batholith (2702.5–2705.5 Ma).

It is possible that Pirie's (1982) proposal that the deposit was formed at moderate to shallow depth and then metamorphosed to amphibolite grade is correct. Alternatively, the alteration may also be the result of two distinct hydrothermal events as proposed for the Campbell-Goldcorp deposit (McGeehan and Hodgson, 1982; Mathieson and Hodgson, 1984). An early synvolcanic (volcanogenic-massive-sulphide-related), large-scale alteration event could correspond to the aluminous outer alteration event and be related to the eruption of 2741 Ma Confederation assemblage dacite units. In such a model, this event would be followed by an auriferous event, characterized by the inner alteration and responsible for the formation of the deposit. The aluminous outer alteration which has affected the Madsen area is atypical of syn-amphibolite gold deposits hosted by mafic rocks (e.g. Witt and Vanderhor, 1998) and supports the presence of two different styles of hydrothermal systems as suggested above.

This preliminary report indicates that the notion that the Madsen deposit is genetically directly controlled by D_2 ductile shear zones is incorrect and its genetic relationship with the Killala-Baird batholith is inconsistent with age constraints and field relationships. The deposit is probably related to an 'early' alteration and manto-style replacement mineralization which was deformed and partly transposed by D_2 and metamorphosed by the batholith, instead of genetically directly related to them. The timing relationship of the mineralization relative to D_1 remains to be better established.

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